From bicycle crashes to measures

Brief overview of what we know and do not know (yet)

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1. Introduction, objectives and scope

The latest injury and fatality figures show cycling safety to deteriorate in the Netherlands. Every year, about a quarter of all traffic fatalities and more than half of the number of seriously injured road users are cyclists. In the last decade, the number of seriously injured cyclists has even increased by 55%.

The above figures indicate that crashes in which cyclists are involved form a large share of crashes in the Netherlands. As bicycle use is expected to grow over the coming years, and the group of seniors (a vulnerable group of road users) will increase due to population ageing ,the numbers of cycling casualties are expected to rise even further. To stop this negative trend, cycling safety needs to be improved by means of evidence-based prevention strategies. To that end, a National Research Agenda Cycling safety (NOaF) is needed, to identify the current research needs and to indicate high priority research areas. In order to draft such a National Research Agenda, the current knowledge-base on cycling safety needed first to be explored and the knowledge gaps identified. As such a systematic overview of the state of the art was not yet available, we conducted a review of the current literature on cycling safety. This document contains an overview of its main findings. Detailed information can be found in the final report - in Dutch - by Reurings, Vlakveld, Twisk, Dijkstra & Wijnen, (2012). *Van fietsongeval naar maatregelen: Kennis en hiaten.* R-2012-8 Leidschendam: SWOV Stichting Wetenschappelijk Onderzoek Verkeersveiligheid.

However, it should be noted that, at this stage, such an overview of existing knowledge cannot be exhaustive. The width of the subject and the fact that no previous inventories were available to elaborate on may have led to relevant studies being missed. It should also be noted that the reported studies are mostly from the Netherlands; studies from other countries have also been included, whenever available. Because of the Netherlands having a unique cycling culture that greatly differs from that in other countries, results from international studies may not apply to the Dutch situation, and vice versa.

The present overview solely focusses on the direct influencing factors, such as the traffic environment, the cyclists' traffic behaviour, other road users' behaviour, legislation, route choice, weather conditions, traffic intensity, the quality of the bicycle, the crash characteristics of motorized traffic and the quality of post-crash assistance. It complicates matters that these factors are not independent of one another. For instance, road user behaviour is not only influenced by a person's knowledge, motivation and skills, but also by the design of the infrastructure and by the traffic rules that apply. Understanding these interrelationships is not only of importance to analyse the nature of the safety problem itself, but also to select the most effective prevention strategy, and thus to answer the question: 'Which links in the cause-effect chain need to be addressed to achieve the greatest safety effect?' Therefore, we will first present a theoretical framework of these relationships and discuss the implications for prevention.

A further comment concerns the indirect influences on cycling safety. There are several factors outside the traffic system that have a direct influence on cycling safety, such as economy, population ageing, environmental planning, and social relations. The economy, for instance, has an influence on road safety investments and on traffic volumes. Environmental planning determines the locations of facilities, such as schools, work locations and shopping areas, and thus directly influences traffic volumes. Changes in 'lifestyle' influence consumer needs, trips and aspirations. The rise of the mobile phone fills the need to be in touch with others, which has resulted in their use while cycling. This broader context is too wide for including it into a study of this nature. Instead of reviewing these indirect influences, we limit ourselves to discussing the direct influences only. For instance, the safety effects of electric bicycles will be discussed, but not the question of why these bikes have become so popular the last few years. Similarly, the safety consequences of the use of the mobile phone while cycling will be discussed, but not the reasons for the increasing use of mobile phones.

An additional consequence of the exclusion of indirect influences is the exclusion of the mechanisms by which road safety measures get implemented. As a consequence, the study has not looked at road safety policy itself, as, for instance, the way in which policy is organized and choices are made about the implementation of measures. However, the extensive international literature about this subject indicates that factors such as the presence of a central coordinating body, the availability of national data on road crashes, and political commitment to national safety targets are necessary preconditions for effective road safety policy. (OECD-ECMT, 2008). As this involves the entire area of road safety policy and not specifically cycling safety, this has not been dealt with in the present study. For further reading on this topic, see: Bax, De Jong & Koppenjan (2010), OECD-ECMT (2008) and Wegman & Aarts (2005).

2. Theoretical framework

The traffic system entails three main components: the infrastructure, the vehicles and the road users. The infrastructure makes traffic possible and, in combination with the traffic rules, guides and restricts road user behaviour, and controls interaction. The vehicle makes mobility possible and, on the one hand, meets the demands of the infrastructure (e.g. minimum or maximum speed, braking power, etc.) and, on the other hand, the demands of the road users (e.g. brake levers within easy reach), during actual movement.

2.1. System approach, vulnerability and prevention

Two approaches are to be distinguished with respect to the understanding and prevention of road crashes and fatalities, which differ in the analysis of the problem and the selection of preventive measures. The first, the individual approach, theorizes that people crash, because their personal characteristics and decision-taking results in unsafe road behaviour. The second, the safe-system approach (OECD-ECMT, 2008), assumes that road users crash, because of the user-unfriendly characteristics of the road system. Two observations in road safety are central to both the individual perspective and the safe-system approach, (a) human behaviour is directly or indirectly responsible for an estimated 96% of crashes (Sabey and Taylor, 1980), and (b) road crashes and injuries are not equally distributed in the road user population. Some road users have a higher crash involvement than others (e.g.,Visser et al., 2007; Wåhlberg, 2009). The two approaches have in common that they both identify road user behaviour as an important element in the prevention of crashes, but they differ in the interpretation and implications. Whereas the individual approach aims to adapt road user performance to the demands of the road system, Safe System Approaches (SSA), in concurrence with Reason's theory on human error (1990), consider how these errors are elicited by the traffic system's design.

The System approach has been proven to be the most effective for road safety (OECD-ECMT, 2008). This approach, which comes in many forms, sets out to prevent dangerous situations rather than crashes. In this section this ‘system’ approach will be illustrated by one of the best-known models used in road safety, as well as in industrial safety (see *Figure 1*). This model visualises two essential characteristics of an ‘unsafe’ system. First, the presence of ‘latent failures ‘(the holes) in the different levels of the traffic system, whereby the system as a whole produces failures when all individual barrier weaknesses align, permitting "a trajectory of accident opportunity", so that a hazard passes through all of the holes in all of the defences, leading to a crash. In the causal sequence of human failures that leads to a crash, the model includes both active failures and latent failures. Active failures can be directly linked to an accident, such as the lorry driver overlooking a cyclist's presence in the blind spot. Latent failures include the preconditions for these unsafe acts, such as – in the example of the crash between lorry and cyclist - mixing cyclists with heavy-goods vehicles in busy town areas. Thus, human error may occur from contributory factors in the system that may have lain dormant for a long time, until they finally contribute to the accident.

To date, the system approach has also been effective in reducing the injuries that result from a crash. Especially car occupants have benefitted from the high levels of physical protection that comes with the car itself, owing to features such as safety belts, crumble zones, and airbags. Cyclists, in contrast, are fully exposed to the high-impact forces generated in a crash. Although some developments may offer some protection, such as the cyclist airbag on the car bonnet or helmets for cyclists, it is hard to envisage protection systems for cyclists of the same standards as that for car occupants. The vulnerability of cyclists implies that the prevention of collisions of any kind is of even more paramount importance for the reduction of injuries among cyclists, than it is for car occupants.

With respect to the prevention of crashes, one often tends to look at road-user level only: 'the unsafe actions of the road users'. This appears logical because research has also shown that an estimated 95% of all crashes resulted from an unsafe human action (Sabey & Taylor, 1980). It does not follow, however, that measures aimed at those unsafe actions are also the most effective. As the model illustrates, it is more effective to eliminate the errors that are enclosed in the design (system, design, infrastructure and vehicles) than to prevent human errors. Knowledge from cognitive ergonomics also confirms that it is almost impossible to eradicate human error by means of interventions directed at the road user, instead of a traffic system designed in such a manner that it is tailored towards the road user's capabilities and shortcomings.

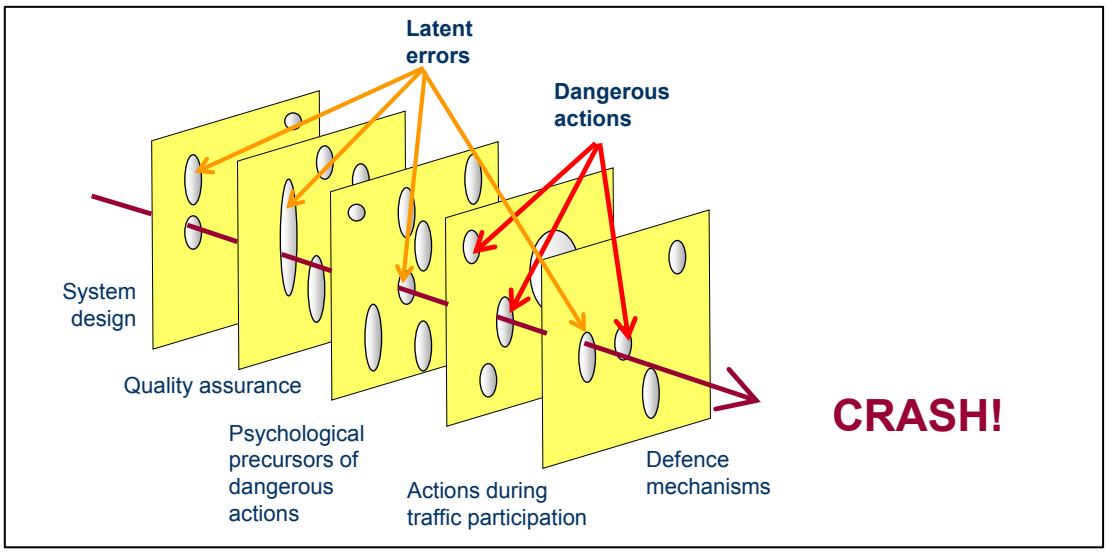

Figure 1. *Development of a crash as the consequence of latent errors and unsafe actions in the different elements that constitute road traffic*

This approach also illustrates that in order to design a safe road system, one should not base prevention strategies on crashes and injuries alone, but also on the identification of latent failures. For example, to estimate the effect of speed on safety, it is sufficient to know the prevalence of speeding on the road, and to identify 'latent failures' in the system that contribute to drivers driving too fast, so that it is not necessary to 'wait for a crash to happen'. Moreover, the proportion of speeding drivers can serve as an indicator of the system's safety. Indicators of this type have shown to increase crash risk, and are often referred to as Safety Performance Indicator (SPI), and can be used to identify the 'latent' failures in the system. For car drivers, a wide range of SPIs has been developed, for instance on speeding, alcohol use, safety belt wearing. As yet, hardly any good SPIs are available for cycling safety. SPIs that may be relevant for cycling safety are factors such as the road lengths that meet the criterion 'safe speeds', the proportion of cyclists that use adequate bicycle lighting, the proportion of bicycles that are in good technical condition, the proportion of bicycle paths that are well maintained and have no dangerous obstacles.

2.2. Conclusions for research agenda

Insight in the interrelations between the parts that form the traffic system, the characteristics of the crash process, and the possibilities for prevention results in the following conclusions to prioritize the subjects on the research agenda:

- As there are only few possibilities to protect cyclists from sustaining injuries in a crash, the first priority – even more so than for car occupants – is to prevent crashes.
- Although human errors are the main cause of traffic crashes, most of the safety benefits lie in the elimination of 'latent failures' in the traffic system – infrastructure, vehicles, and legislation – so that road users commit fewer errors and, if they do, that these errors do not lead to serious injury.
- The effects of the latent failures can be quantified by using SPIs rather than crashes, thus allowing a pro-active approach.
- SPIs for cycling safety need to be developed.

3. Data availability, quality and needs

Data on crashes is important to gain insight into: a) the magnitude and nature of the road safety problem for cyclists, the high risk groups, b) the active failures causing crashes and c) the latent failures in the road system (SPIs). To be able to correct for external influences, data on matters like distances cycled, trips and reasons for making trips, population structure, and size and nature of the vehicle fleet is also important. This section presents an overview of the characteristics and reliability of the available data.

3.1. Data requirements

Crash and injury data

To date, the Netherlands has no registration of bicycle crashes of sufficient quality.. In fact, BRON - the road crash data file based on the police registration - is intended to serve this purpose, but the registration rates of bicycle crashes, and especially bicycle-only crashes and those without serious injury, are far too low. Therefore, the number of fatalities, serious road injuries, and A&E casualties among cyclists are annually measured on the basis of three different registrations: the Dutch mortality registration (DMR), the Dutch Hospital Data (DHD) for serious road injuries, and the Injury Information System (LIS) for the A&E casualties. These registrations actually serve different purposes and each registration contains only information that is relevant for its purpose. For instance, the DHD contains detailed information on the injury, and some information on the crash conditions, while the police registration is superficial on injury characteristics and detailed on crash conditions. Presently, combined information from BRON, DMR and DHD provides reliable information about the magnitude of safety problems among cyclists, by age and gender, but too little information on crash conditions.

Also the available information on crash conditions (active failures) in BRON differs by crash type and injury severity. In three-quarters of the fatal crashes involving a cyclist and a motor

vehicle, detailed background information is available in the police registration (BRON). If the cyclist was seriously injured in a crash and no motor vehicle was involved, this proportion drops to a meagre 4%. The low registration rate of the latter crash type matters, because this crash type is responsible for the vast majority of serious injuries among cyclists, and because this number is strongly rising. This problem of under-registration is partly overcome by regular supplementary surveys among injured cyclists, receiving treatments in A&E departments. The question is whether data generated by this survey method is of the same quality as data from the police registration. The limitation of these surveys are the relatively small samples, which limits the possibility of disaggregation of the data, for instance by type of bicycle (e.g., e-bike), trip motive (e.g., working out), trip condition (e.g., in daylight or darkness), or cyclist characteristics (e.g., use of alcohol). A second limitation is that the reliability of questionnaire studies may be limited, due to selective low response rates. Certain subgroups – for instance those cyclists who have suffered serious injuries or those who consider themselves to blame for the accidents may return the questionnaire less frequently than others do, thereby distorting the findings from the study. As the registration rates of bicycle crashes in BRON are still falling, research is needed into the question whether and how questionnaire studies, and, in line with this, crash hotlines, could complement the police registration and yield full and reliable information, especially in relation to the exact location of the crash, the layout of the infrastructure, the local regulations, and the interactions with other road users.

In comparison to BRON, the medical files (DHD and LIS) are superficial on accident characteristics, but far more detailed on the type and severity of the injuries. This makes it possible to study injury severity in relation to crash type and to assess the protective effects of passive safety measures, such as the external cycle airbag (SafeCaP), bicycle helmets, but also physically forgiving road sides.

To date, none of the three databases are geared towards the safety impacts of new developments. For example, the crash involvement of ‘electric vehicles’, such as scooters, bicycles, cars and trucks on safety cannot be systematically monitored, while they may have considerable impact. For instance, electric bicycles are used by a vulnerable group of senior road users, and their higher speed may increase crash risk and injuries; electric cars, travelling at low speeds do not generate ‘sound’ and may not be heard by cyclists and pedestrians. Research will vastly be facilitated by crash, injury and travelling databases in which the characteristics of these ‘new developments’ can (temporarily) be registered.

Travelling behaviour (exposure)

Road safety policy aims to make cycling safer, and not to discourage cycling. Thus, in policy terms, cycling risk – i.e. injuries per distance travelled – should be reduced. To achieve this objective, not only casualties need to be registered, but also the amount of cycling. The mobility database (OViN) contains the average annual mileage per age group, gender, trip length, and time. Unfortunately, the accuracy of the mobility data is possibly deteriorating as the national averages for cycling are estimated on the basis of an ever smaller number of cycling trips.

Safety Performance Indicators

Reliable SPIs are a precondition for pro-active cycling policy, but, to date, these have not been developed yet for cycling. Important indicators are the local speed limit and the actual driving speeds. The concept 'safe speeds' can here be used as a guideline. In this case, safe speeds means in crashes between road users, there is a strong likelihood of survival. The safe speeds are known for pedestrians and car occupants. (Table 1).

Road types in combination with permitted road users	Safe speed (km/h)
Roads with possible conflicts between cars and unprotected road users	30
Intersections with possible lateral conflicts between cars	50
Roads with possible lateral conflicts between cars	70
Roads where frontal or lateral conflicts between road users are not possible	≥ 100

Table 1. *Proposal for permitted safe maximum speeds for cars, by different crash scenarios (Wegman & Aarts, 2005)*

Although cyclists and pedestrians are both unprotected road users, the safe speeds are likely to be different for cyclists. The SPIs and 'safe speeds' are examples of a more pro-active approach towards road safety, in the sense that dangerous situations are eliminated at the root.

3.2. Conclusions for the research agenda

Data about crashes, the latent system errors (the Safety Performance Indicators or SPIs), exposure, such as distances cycled, and social developments such as population structure, are necessary to obtain insight in the causes and the development of safety for cycling in the Netherlands. Most of this data is of insufficient quality where cyclists are concerned. Obtaining reliable data is therefore an important activity on the research agenda.

- Development of a reliable registration of lack of cycling safety. This is especially the case for injured cyclists in crashes not involving motor vehicles. It should be investigated if and how questionnaires and hotlines can be used to obtain reliable and complete information.
- Timely adjustment of registrations that allow flexible responses to new developments in relation with cycling safety. Examples are the registration of the electric bicycle as a separate category in crashes or mobile phone use while cycling.
- Development and building of registration files with SPIs for cycling safety. For example, a file which indicates per town which proportion of intersections has a 'safe speed limit'.

4. Magnitude and nature

4.1. Injury severity and the long-term consequences

Casualties due to bicycle crashes constitute an increasing share in the number of road fatalities and serious road injuries. This chapter presents an overview of the most important characteristics of these injuries and crashes.

Although the number of fatalities among cyclists diminishes, albeit less fast than is the case for other road users, the number of seriously injured cyclists increases steadily. This increase is mainly due to the increase in seriously injured cyclists in non-motor-vehicle crashes and to the increasing proportion of senior cyclists. Not only does the number of senior cyclists increase, but they also cycle more. Furthermore, the decline of the number of seriously injured cyclists in motor-vehicle crashes has come to a standstill. This applies to all cyclists, not only to seniors. Reurings et al. (2012) suggest some answers to the question how this can be explained, among which distraction and the large amount of traffic on the bicycle paths. The motor-vehicle crashes are also characterized by the relatively large number of fatalities among cyclists of secondary school age.

Motor-vehicle crashes and non-motor-vehicle crashes with cyclists also differ in the type of injury. In motor-vehicle crashes cyclists sustain brain injury most frequently. In non-motor-vehicle crashes leg injury is most frequent. Moreover, this latter group also sustains injuries to the arms twice as often as the first group. A possible explanation may be that cyclists try to break their fall when they topple over, while such protective action does not occur in a collision with a motor vehicle.

To gain insight into the long-lasting effects of the injuries on wellbeing and functioning, an analysis was made of the number of years that injured cyclists have to live with permanent

injury: Years Lived with Disability (YLD). This showed that bicycle crashes are responsible for just less than half the YLD of all road casualties. This indicates that not only half of the serious road injuries are cyclists, but also that the permanent consequences are at least as serious for them as they are for other road casualties.

4.2. Crash characteristics

Most cyclists (60%) die in urban crashes. In addition, intersections are the most dangerous locations; both urban (65%) and rural (52%). with respect to seriously injured cyclists, data is only available of crashes with motor vehicles. The majority of these crashes also occur in urban areas (81%), almost three-quarters of which happen at intersections. This number is approximately half with respect to rural crashes. The location of non-motor-vehicle crashes is unknown. As the location data is lacking, it is difficult to obtain an idea of the underlying causes and the role of local conditions like infrastructure and traffic volume in this type of crash.

Cycling safety, even more so than the safety of motorized traffic, is affected by the weather. On the one hand, this may be observed in cyclist mobility (there is more cycling in nice weather) and, on the other hand, weather can be seen to influence crash factors like visibility, vision, and controllability of vehicles. The police registration contains information about the weather conditions at the time of the crash, but the precise relation between weather and crash rate cannot be determined, because the mobility data is insufficiently accurate.

This data, however, is accurate enough to indicate seasonal effects. In crashes not involving motorized vehicles, the risk of a cyclist being seriously injured is lower in winter than it is in summer. Slippery winter roads, therefore, do not have the expected effect on the non-motorized-vehicle crashes; also in winters with heavy snowfall. A possible explanation for this unexpected difference is the type of cyclist. It may be the case that cyclists with a high risk of falling, such as senior cyclists and racing cyclists, use their bikes more frequently in summer than they do in winter. For motor vehicle crashes this relation is just the opposite. The risk of a cyclist being seriously injured in a crash with a motor vehicle is higher in winter than it is in summer. This also has many possible explanations, such as bad vision and visibility, and the worse controllability of vehicles.

4.3. Cycling mobility and risk development

Cycling increases in the Netherlands, but there are large differences between demographic groups. For example: men cycle more than women, but women travel a greater proportion of their mobility by bicycle than men do. Secondary school pupils cycle more than any other age group: they travel almost one-third of their total mobility by bicycle.

After correction of the crash data for these differences in mobility, the fatality rate (fatalities per distance travelled) for cyclists appears to have gone down, but this decline is smaller than that of car occupants, for instance. On the other hand, the risk of being seriously injured in a crash not involving a motorized vehicle, greatly increased for cyclists, whereas that risk

remained almost constant for motor-vehicle crashes., Cyclists older than 75 have the highest injury rate of all the different age groups. This is almost six times higher than the injury rate of the group 18 to 54-year olds, for example.

4.4. Conclusions for the research agenda

Among cyclists in general, a number of subgroups can be distinguished that are subject to an even more unfavourable development than average within the category of cyclists. The research agenda should pay extra attention to these groups in coming years.

- The number of seriously injured cyclists has risen considerably in recent years. This increase is particularly noticeable for crashes in which no motor vehicles are involved. Increasing cycling mobility and social influences like the sharp rise in the ageing population can only partially explain this increase. Research needs to be done to find the underlying causes.
- Youths constitute a relatively large share of the cyclists who die in crashes with motor vehicles.. More insight into the underlying causes of these crashes is necessary.
- The largest increase in cyclist casualties is among senior road users. It must be determined what causes this high risk of cyclists aged 75 and over.

5. Risk-contributing factors

For safe use of the traffic system, the road user is dependent on the extent to which vehicle, infrastructure and legislation are tailored to his mental and physical abilities. That is why this section will first discuss the competencies, task capability, and safety motivation of cyclists in general, and will then proceed to take a closer look at safety and the characteristics of different age groups.

5.1. The cyclist

5.1.1. The cycling task

Like all other traffic tasks, the cycling task can also be divided into decision-taking at three levels: the strategic, tactical and operational level. In this three-level hierarchy, the decisions taken at the higher levels restrict the decisions at the lower levels. The time available for taking decisions increases as the level gets higher (from milliseconds to nearly unlimited).

The operational level is the lowest level and comprises vehicle skills. To control the vehicle the cyclist has to perform tasks, such as getting on and off the bike, staying on course, indicating direction, cycling with one hand at the handlebars, looking across the shoulder, keeping balance, controlling speed, braking, cycling straight ahead, and changing direction. These types of action only take milliseconds. The tactical level concerns the cyclist's manoeuvres. An example of a manoeuvre is ‘turning left at an intersection’ or ‘crossing a road’. In addition to the vehicle skills mentioned earlier, this also requires skills such as correct application of the traffic rules, estimating the speeds of the other traffic, and anticipating dangerous situations. At this level, the available time is also short: seconds. The strategic level concerns skills about when and how a journey is made. This requires skills like choosing a route, estimating the duration of the journey, and taking account of specific conditions, like the weather. The cyclist can take a generous amount of time to make these choices.

Competencies

Performing the cycling task makes large demands on the cyclist's skills. Yet, experienced cyclists often seem to participate in traffic 'on autopilot' and to barely have a problem with carrying out a multitude of actions simultaneously. In contrast with what is commonly assumed, this behaviour is often safer than when everything still needs to be reasoned and every action still requires consideration. An absolute beginner has not yet developed these routines and is still slow and error-prone. It is also - more or less - impossible for a novice cyclist to perform tasks simultaneously. It takes plenty of exercise to carry out these (sub) tasks on autopilot. For an experienced cyclist, the actions at the operational level are for the major part automated. Decisions on the tactical level can also be taken automatically if the situation is familiar. When confronted with an unknown traffic situation, the reaction will usually be a deliberate choice.

Car drivers are known not to have reached expert levels until they have driven 100,000 kilometres. The distance cyclists have to travel to achieve this is yet unknown. An important precondition for automatic behaviour is the predictability of the task environment. That two-way bicycle paths are less safe, for example, could be due to the fact that cyclists come from a direction the driver does not expect.

Hazard perception, Calibration/state awareness

The most important traffic skill may be the timely detection, recognition and prediction of hazards. This higher-order skill only develops slowly and does not reach the 'expert level' for quite some time. For this reason a hazard-perception test has now been made part of the theory examination for the driver's licence. Little research has so far been done into hazard perception among cyclists. A study among pupils of the last grade in primary school, however, indicated that although these youths are perfectly capable of identifying the blind spot and the hazardous locations in the vicinity of trucks, they are unable to translate this knowledge into safe behaviour in those traffic situations. Training seems to have an effect, but cannot prevent unsafe behaviour in the majority of these situations. Therefore, knowledge about hazard perception among cyclists and the possibilities for improvement are important building blocks for educational interventions.

Road users not only need to assess the risks, they also need to estimate their own capability to control the hazards (calibration/state awareness). Little is known about the cyclists' capabilities to do so, which may be particularly important for the elderly and people suffering from progressive cognitive disorders like dementia. Are they aware of the fact that things are not quite as they used to be? For this latter group the illness is known to not only affect memory functions, but also the perception of one's own functioning.

An important psychological process, and a special form of calibration, is behavioural adaptation. This phenomenon, in which road users display unsafe behaviour because they feel safe, has immediate consequences for the effectiveness of measures. These types of effects have, for example, been observed in shorter headway distances when driving with an ABS system, and higher speeds when a seatbelt is used. For cyclists, study has only been made of behavioural adaptation in relation with bicycle helmet use. Those cyclists generally

wearing a helmet were asked to cycle down a hill not wearing one. They felt unsafe and went downhill more carefully than while wearing a helmet.

Cycle fitness

The safety level at which a task is performed is not only determined by skills, but also depends on the physical and mental state: the capability. Factors with a negative effect on task performance are, for example, fatigue and physical and mental disorders. Little is known about the effect on cyclists. We do know, however, that certain disorders are more frequent in specific age groups. ADHD, for instance, is frequent among young people, whereas different types of dementia are often found among seniors. Both disorders are known to greatly increase the crash rate for drivers of motor vehicles. It is not known whether this is also the case for cyclists, but given the high prevalence, further study is recommended.

The task capability is not only affected by physical disorders, but also by the use of psycho-active substances. The most popular substance, alcohol, increases the crash rate for cyclists to the same extent as for drivers. However, at blood alcohol concentrations of 0.02 % and over, the crash rate for cyclists increases more strongly than the crash rate for drivers. The extent to which cycling under the influence of alcohol occurs is unclear. However, the statistics indicate that a large proportion of the cyclists who visit the A&E department during weekend nights are under the influence of alcohol. The effect that various drugs may have on the crash rate of cyclists has, to our knowledge, not yet been investigated.

The few studies that investigated the effect of medicine use indicate that sleeping pills and tranquilizers strongly increase the crash rate of senior cyclists.

It must be noted that far fewer measures can be taken to deal with reduced fitness among cyclists to participate in traffic than is the case among drivers. Drivers who are no longer fit to drive lose their driving licence, whereas no such measure exists for cyclists unfit to participate in traffic This difference may be explained by the differences in social responsibility: other than drivers, cyclists are generally the ones who are injured in crashes and they rarely cause serious injury to other road users.

Hazardous behaviour: self-chosen exposure to danger

The exposure to danger is not only determined by the task capabilities and fitness, but also by the cyclist's own choices: willingness to obey the rules and to behave in such a way that one's own skills are not exceeded. The first choice relates to the official traffic rules, the second mainly concerns 'safe' behaviour. Traffic rules are intended to improve the traffic flow and ensure safe travel for all road users. Safe behaviour goes beyond obeying the rules, and concerns the prevention of hazardous situations. For example: instead of crossing a busy road when the view is obstructed, the cyclist chooses to use a bicycle tunnel a bit further down the road.

The willingness to obey the rules is partly determined by how these rules are perceived. As traffic rules are in conflict with self-interest and are not found to affect safety, they are often

offended against. Not everyone reacts in the same manner; roughly three types can be distinguished: the 'vicar', who believes one should keep to the rules and therefore does not require enforcement (intrinsic motivation); the 'merchant', who weighs the pros and cons of the offence, including the risk of a fine or crash (instrumental motivation), and the 'soldier' who only obeys the rules from fear of punishment (extrinsic motivation) (Van Reenen, 2000).

Although many of the theories about enforcement are based on the fact that offences are mainly the result of such conscious considerations, indications are increasingly found that these considerations have to a great extent also become ingrained. Once they have become automatisms, they are very difficult to change: 'what's learnt in the cradle lasts till the tomb' applies here.

Little is known about how often cyclists offend against the traffic rules and about the reasons for their offending behaviour. For example, whereas drivers are checked regularly for drink-driving or speeding and their numbers are known, this is not the case for cyclists. With respect to cyclists, this type of data is only available about whether or not they use bicycle lights. Partly as a result of campaigns and increased police enforcement, cyclists have shown increasingly to use bicycle lights in the dark. This result is similar to that for campaigns that were aimed at drivers: police enforcement was found to be an important part of effective campaigns.

Unsafe behaviour caused by distraction deserves a special mention. Although no concrete offence is involved, research indicates that distraction is an important risk factor, for instance using the phone while driving. Recently, studies have been conducted into making phone calls and listening to music while cycling. It was found that making a phone call slightly increases the crash rate, whereas sending a text message seems to have a strong negative effect on the crash rate.

In addition to dangerous cycling behaviour, cyclists may also be exposed to hazards at a strategic level by a poor technical state of their bicycle. However, crash analyses show that technical defects play a role in only a small proportion of the crashes. This issue requires no further study.

Interaction with and the behaviour of other road users

Cycling safety does not only depend on the behaviour of cyclists themselves, but also on that of other road users. Certain types of interactions between cyclists and motorized traffic have already been studied. For example, much is already known about the occurrence of blind-spot crashes and effective measures have been implemented which have reduced the number of cycling casualties due to this crash type by about 40%.

Not much research has been carried out into other conflict types involving motorized vehicles and cyclists. Little is also known about the ways other road users could be taught how to improve their anticipation of cyclists in traffic. For example, is it useful to use the driver training for a special training of hazard anticipation in relation to cyclists?

The speed driven by motor vehicles may be the most important factor for cyclist safety. Many studies indicate that the speed limits are often ignored, especially if the 'feel' of the infrastructural layout does not conform to the speed limit at the location. Examples are the Zones 30 with a 'sober' layout. In zones with a sober layout, the lowering of the limit from 50 km/h to 30 km/h has mainly been accomplished by placing a sign indicating the 30km/h limit, without any other adaptations of the infrastructure. It has been found that the safety of vulnerable road users in Zones 30 with a sober layout is worse than in Zones 30 where the layout is used to more or less enforce the required speed.

In addition to infrastructural adaptations, enforcement of the speeds driven is also very effective. Evaluation studies indicate that speed enforcement in urban areas can reduce the number of road fatalities by as much as between 38 and 59%. The effect on road injuries is somewhat smaller. However, these are total effects, not divided by mode of transport. Without this disaggregation, the question remains how much these measures are in fact of benefit to the cyclist. The same is the case with enforcement of red-light running and alcohol use. Both are very effective, but how effective they are specifically for cyclists is not known.

5.1.2. Age groups

Major differences occur among cyclists in the way they carry out their traffic tasks. Age plays a major part in these differences, as well as the extent in which cyclists become casualties and sustain injuries. The sections below therefore discuss various age groups.

Children: a new approach required, but how?

Comparatively speaking, the number of casualties among young cyclists in the 0-11 age category is fairly high and the same applies for their risk. This is logical because they are fairly inexperienced cyclists who still have much to learn. Thanks to the many traffic-calmed residential areas, they can learn safely, provided they do not sustain serious injuries when toppling over with their bicycle. They may benefit from wearing a bicycle helmet. It is important for the physical development of this age group in particular to be active, and cycling mobility is an important step towards their independence.

Things change considerably when children leave residential areas, because they then have to participate in traffic actively. It is not always easy for parents to assess their children's abilities. They can choose between two options:

- Reducing the exposure as long as possible, which may result in limiting their child's independence;
- Training and guidance until the child has fully learnt.

Not much is known about the preferred method, so that parents have little to fall back upon. More so than in the past, parents seem to prefer to transport their children in their car, rather than have them cycle on their own. Theoretically speaking, this might keep them safer during their primary school period, but they will be completely inexperienced cyclists when they go to secondary school.

Special attention should be paid to children from deprived families, among whom non-indigenous families. International studies indicate that children from deprived families are

more often involved in crashes than children from more well-to-do families. Whether this situation also applies for the Netherlands is uncertain, because this has rarely been investigated.

In addition to generic measures, traffic education is used to increase children's safety. Not enough research has been conducted into the effects of traffic education on behaviour and crash rate of cyclists, and those studies carried out show that the effects are limited. Besides, also programmes were implemented that turn out to be ineffective. Evaluation studies are required in order to assess how effective programmes are and, subsequently, to improve the less effective programmes. For instance, it is noticeable that a programme such as the 'traffic exam', which primary school pupils have been taught for years and years, has never been evaluated, so that its effects are not known. Special attention is required for the development of hazard perception and the possibilities to teach it, possible supported by parents.

For the 0-11 age group, research should focus on:

- the relation between socio-economic status and road safety of children;
- the effects of cycling experience gathered during the primary school period on later crash involvement;
- the development of hazard perception and how education may be effective;
- The role of parents in the learning process.

Youths 12-24 years: on the right track

A major part of all cyclist fatalities and seriously injured occurs in the 12-24 age group. However, this group cycles a great deal, so that the fatality rate (crash per distance travelled) is only slightly higher than that for middle-aged cyclists, and the crash rate with serious injury is even slightly lower than the rate for middle-aged cyclists. This is noteworthy, because risk-taking behaviour among adolescents (10 to 17 years) highly increases, compared with children and adults. Recent research into brain development has indicated that this is probably the result of brains not yet being fully formed, so that impulse control is insufficient, whereas the drive to experience thrills highly increases under the influence of puberty hormones. Parents increasingly withdraw from educating them and friends begin to play an increasingly significant role. A number of studies among young car drivers has indicated that youths tend to behave more hazardously among friends than they do on their own.

Yet, not only do these kinds of lifestyle factors play a part, also inexperience a plays a role. When they exchange primary school, situated in their familiar residential area, for the secondary school, located further away and often in busy town centres, they meet unfamiliar and more complex traffic situations. It remains to be seen how capable they will be to timely recognize and prevent the dangers resulting from these more complex traffic situations. Indications are that their hazard perception has not yet been sufficiently developed. The question is how and if this hazard perception can be improved.

Youths are involved in crashes with motor vehicles more often than other age groups are. The outcome of this type of crash is often also more serious. It is not clear how to explain this more frequent involvement. The patterns discerned do not indicate that their own behaviour and, in particular, their youthful over-confidence contributes to this type of crash

specifically. It has been noted that with practically all modes of transport over-confidence plays a role among men particularly, so that risks are often higher among men than among women. Yet, quite remarkably, this gender difference does not apply to young cyclists. Among this group of road users, boys and girls are involved at equal measure. It is to be recommended to investigate this type of crash (motor vehicle-bicycle) more fully, and not only to focus on the behaviour of the actual cyclist, but also on the behaviour of drivers of motorized vehicles.

Single bicycle crashes involving alcohol use are a special category in this age group. Our analyses show that alcohol plays a role in circa 50% of the single bicycle crashes of 18-24-year olds during weekend nights. As the crash rate increases extremely with very high alcohol percentages (2 pro mille and over), this problem could also be the consequence of the increasing, excessive alcohol use among this age group, which does not only result in bicycle crashes, but also in other negative aspects, such as aggression, damages and alcohol poisoning. Should prevention, therefore, mainly focus on road safety or does it require a more generic approach and outlook, including all aspects concerning alcohol abuse?

For the 12-24 age group, research should focus on:

- the development of hazardous behaviour among young adolescents;
- the development and training of hazard perception;
- the cause of the rather substantial involvement in crashes with motor vehicles;
- an assessment of the problem of excessive alcohol use and cycling safety.

Senior cyclists: persistent problem and no insight in the cause

An increasing number of casualties occurs among senior cyclists, as a result of the population ageing, the number of seniors growing, and the increasing popularity of cycling among this age group. The crash figures give reason for distinguishing three groups of senior cyclists: 55-65-year olds, 65-74-year olds and those over 75. Risks begin to increase for the 55-65-age category. This trend continuous among the 65-74-year olds, but especially the group of 75 and over dominates the statistics and runs the highest risk, probably because of high physical vulnerability. Because of this physical vulnerability, senior cyclists suffer more severe injuries in a cycle crash, than a younger person would. Moreover, seniors also less easily recover from these injuries that may more frequently result in medical complications leading to death. We compared the vulnerability of senior cyclists with that of senior car occupants. It showed that the protective characteristics of cars are the reason that physical vulnerability only becomes a problem for seniors of 75 and over, whereas it already plays a role for cyclist of 55 and over. Moreover, vulnerability increases far more than is the case with car occupants of the same age.

There is actually also a difference among men and women over 75 in terms of vulnerability. Women die less often than men do, although they sustain serious injuries more often. We did not find a clear explanation for this difference. Women may be more resilient, or crashes involving men are more serious and their injuries more severe as a result.

Looking at the cause of crashes, on the tactical level seniors often tend to have difficulties turning left. In a questionnaire study (the 'ALVO questionnaire) among patients who ended up in an A&E department after a crash, 25% (125) of the respondents were senior cyclists (55+). For a quarter of them (31) the injury turned out to be the result of a fall while getting on or off the bicycle (operational level). Among the younger age groups this made up a share of no more than 4%. Yet, this outcome directly illustrates the limitations of the data, because this analysis is in fact based on a mere 125 senior respondents.

With the exception of the negative effect of sleeping tablets and tranquilizers, no other results have been detected that offer insight in the underlying causes of crashes involving senior cyclists. Not much is known about the effect of functional limitations. When growing older, vision and hearing diminish, muscle power is reduced, and chronic disorders increase. Besides, simultaneously processing information becomes more difficult for seniors and their reaction speed diminishes. Hardly any research has been conducted into the influences of all these aspects on the safety of senior cyclists. As on-going functional limitations are practically unavoidable in the aging process, the possible cause can hardly be ameliorated, other than by buying glasses and a hearing aid in time. The most favourable options for interventions are the great willingness of seniors to compensate for their limitations: for instance, choosing safer routes without complex road crossings, avoiding rush hours. Senior car drivers show their compensation strategies to be less effective than might in principle be possible, because seniors wrongly assume what is 'safe'. They think that, objectively speaking, the safe motorways are hazardous and therefore tend to choose routes on the 80/km/hour roads that are objectively speaking more hazardous. Misconception of this nature can be addressed using publicity campaigns, medical counselling, and a visit to a mobility centre.

Nevertheless, it remains arguable whether it is a traffic safety problem that the dangers for cyclists of 75 and over are so much more substantial than those for younger seniors. It might also be considered a general 'aging problem', which not only expresses itself as falls on the public road, but also as falls in and around the house. This could mean for the approach to be more all-inclusive: not an approach focussed on traffic, but one focussed on the general functioning of seniors. Examples are programmes aiming at improving balance and mobility (through sport and dance, for instance), programmes focussed on nutrition with the goal to keep the bone structure in good condition, and programmes focussed on general practitioners, geriatric doctors and pharmacists in order to reduce the harmful side effects of medication for seniors (e.g. over-dosing or adverse combinations of medicines) to a minimum.

For the senior cyclists, research should be focussed on the following question:

- How can seniors continue to cycle safely much longer? Could this, for instance, be possible by slowing down loss of function, by maintaining a high level of capability, and to adapt the task environment – such as the lay-out of the infrastructure and the bicycle itself?

5.2. The bicycle

Bicycle type

Other than is the case with motor vehicles, the bicycle is not subjected to a type certification, but is assembled from tested and certified components. The bicycle therefore comes in many types. In its current shape, the bicycle is not really different from what it was decades ago. Not many studies can be found about the bicycle as a vehicle. Should innovations have occurred, their safety effects have not been investigated or documented. Nevertheless, theoretically speaking, a number of characteristics of the current bicycle could be optimized. It may be argued that the bicycle should be made more stable, so that cyclists, and especially senior cyclists, will fall off their bicycles less frequently. It can also be questioned how useful and necessary the specific men's model is. Our crash analyses indicate that men, after the age of 55, show a much greater injury rate than women and younger men (if corrected for the distance travelled). It is plausible that the centre bar hinders easily getting on and off the bicycle when one gets older, especially when it is necessary to react to emergency manoeuvres quickly. A third question is whether the braking system could be optimized, so that the vehicle is more stable during a braking activity. Identical lack of knowledge is also found with respect to bicycle components that cause additional injuries (e.g. 'handlebars in stomach'). Many cyclists report that they slid off the pedals, which may indicate that the grip is insufficient in certain circumstances.

The 'electric bicycle' is a new development. This bicycle is powered to assist cycling with a maximum speed of circa 25 km/hr. Its use is rapidly increasing, especially among seniors, and so is the concern about the safety of the vehicle. As the bicycle is powered, it is possible to cycle faster than on a traditional bicycle with the same physical effort. This 'ease' may also be a motive to cycle more often, and also under circumstances that would have been avoided on a traditional bicycle (e.g. with strong winds). Research should indicate whether the electric bicycle entails a greater risk (casualties per distance travelled) compared with the traditional bicycle, and whether cycling with an electric bike increases the risk for seniors.

Bicycle visibility and conspicuity

Cycling in the dark involves a greater risk than cycling during daylight. A (proper) bicycle light reduces the crash rate. It is therefore interesting to investigate the requirements that bicycle lights should meet to supports the cyclist's visibility, as well as the cyclist's vision, sufficiently. For instance, could it be an extra benefit if cyclists had the choice of various luminous intensities, the way car drivers have? The current bicycle reflectors positively contribute to safety. Question is whether additional benefits can be expected from further applications regarding this issue. A front reflector is expected to have added value.

Passive safety and bicycle helmets

A discussion has been going on for years about benefit and need of bicycle helmets. In principle, quite some data has been gathered about this subject, and searching in Google Scholar yields thousands of relevant articles. However, a number of questions, relevant for the 'benefit-and-need discussion', seems to have been answered unsatisfactorily. One relevant question, for instance, concerns the actual protection of helmets with respect to type of crash and road user. In other words, in which type of crashes does the helmet offer

sufficient protection? A second question concerns the functionality of the helmet. Do the current, certified helmets actually offer sufficient comfort and protection? This knowledge is relevant in order to inform consumers about the benefit of wearing a helmet and to be able to consider the safety effect and the undesirable side effects. The relation with the bicycle airbag is also relevant in this context. In a crash with a cyclist, this airbag shields the hard surfaces of the front of the car, so that the crash is softened (see next section for further information). Aside from wearing a helmet, the cyclist is hardly capable of otherwise protecting himself against injuries. Therefore, attention also needs to be paid to objects causing injuries in the environment, such as posts and kerbs.

5.3. The crash opponent's vehicle

As motor vehicles are involved in the majority of fatal bicycle crashes, the question is also raised how measures taken with respect to these vehicles may increase the safety of cyclists.

Trucks and busses, with their large size and their drivers' limited vision on the environment, constitute a high risk for vulnerable road users. As further distracting tasks in the cabin play an increasingly large role, it is to be expected that this risk will increase in the future, if no measures are taken. The most effective measure would be the prevention of these unsafe encounters by, for instance, separating bicycle and transport traffic in place and time. Special investments in mirrors and side-shields also turn out to have a positive effect. Nevertheless, on-going measures for vehicles, such as lowered cabins, are essential for trucks and busses to mingle with cyclists and pedestrians safely.

'Silent' electric vehicles. In the context of sustainable mobility, the use of electric vehicles will increase, especially in urban areas. One of the characteristics of these vehicles is that they are far more silent at low speeds, compared to traditional vehicles. Various studies have indicated that sound significantly contributes to 'environmental awareness', i.e. perceiving and localizing an object. For this reason, sound is often used as a warning signal. Pedestrians and cyclists are therefore expected to use sound to determine the presence, speed and direction of motor vehicles. This may therefore explain why, in the US, electric vehicles crash with cyclists and pedestrians more often than traditional vehicles do. We can ask if and how sound is relevant in the distribution of attention by vulnerable road users and which characteristics of sound they use.

Cycle-friendly cars. Despite the reduction in the number of crashes between cyclists and motor vehicles over the years, it still remains an important crash category, as the injuries from this crash type are far more serious than those from other crash types. Thus, the question is how design and functionality of cars could be altered, so that cyclists are less frequently overlooked and the outcome of crashes becomes less severe. The bicycle airbag is a first development for the good, but will only be effective with head-on collisions, not with side impacts. Also the current developments in the field of Automatic Emergency Braking, whereby the car detects a cyclists, and brakes automatically if the driver fails to react adequately, may save lives.

Intelligent speed assistance (ISA) can ensure that a motor vehicle will not drive faster than the locally permitted speed limit. The two types of ISA systems, passive and active, differ in that passive systems simply warn the driver of the vehicle travelling at a speed in excess of the speed limit, while active systems intervene and automatically correct the vehicle's speed to conform with the speed limit. Passive systems are generally driver-advisory systems. They only alert and inform the driver about the speed limit, but do not intervene. Active ISA systems actually reduce or limit the vehicle's speed automatically by manipulating the engine and/or braking systems. Especially the active type has great potential for the safety of vulnerable road users, especially in combination with 'safe speed limits'. Despite this great potential of active ISA it is only a future prospect, because the political and social support for this measure is very limited.

5.4. Road infrastructure and legislation

Rather a great deal is known about the effect of the quality of the (cycling) infrastructure on cycling safety. For instance, studies have been conducted with regard to the effects of Zones 30 and 60, the construction of bicycle tracks and lanes, prohibition of parking in or along the road, applying exit constructions, roundabouts, cycle paths in two directions, and raised intersections. The effects of these kinds of measure vary from 10 to 60% reduction in casualties. A limitation of these studies is that some are very old and may be out of date (e.g., the study on cycle tracks had been carried out before the moped was moved from the cycle track to the main road). Furthermore, the effects have been calculated as the total number of casualties that have been prevented, but have hardly ever been itemized into effects specifically for cyclists. Finally, the effects of a large number of infrastructural applications remain still unknown, especially of 'new' variations such as unique intersection and roundabout designs and the use of shared space solutions. Positive user experiences have been reported about the latter, but the effects of shared space on the safety of vulnerable road users are unknown for as yet. Still some areas deserve further research attention.

- *The development of safe speed limits for cyclist-motorized traffic interactions.* By disentangling the cycling infrastructure and that of motorized traffic, the areas where both types of traffic mingle have been greatly reduced. But, theoretically speaking, the risk of incidents has increased in areas where both types of traffic again encounter each other, for instance at intersections, crossings and roundabouts. The driving speed of motorized traffic is a factor that both increases crash risk, as well as the severity of the outcome of the crash. On the basis of human physiology, it has been calculated, for car-car crashes, as well as for car-pedestrian crashes, what the chances of survival are, given the impact speed and impact angle. Legal speed limits that are based on these survival rates are known as 'safe speed limits'. These safe speeds and their consequences for the local speed limits have not been calculated and implemented for cyclists.

- *The development of 'safe' design standards for intersections and crossings.* Casualties involving cyclists often occur on intersections and we can ask how the safety of cyclists can be better guaranteed as a result of the layout of the intersections. For instance, safety of signalized intersections turns out to vary substantially among intersections. Greater insight in the underlying causes will be

beneficial for optimizing the layout of this type of intersection. The characteristics of safe intersections have so far not been sufficiently investigated. Finally, extra attention should be paid to the layout of intersections with two-sided bicycle tracks. This type of bicycle track is far less safe than single-sided tracks, probably due to the fact that car drivers do not anticipate cyclist coming from the opposite direction.

- *The development of design solutions for the conflict of function where roads are shared.* Where bicycles and motorized traffic share space, as in Zones 30 or in a Shared Space environment, conflicts occur between the 'residential function' of this type of area – traffic flow being of secondary importance – and the 'cyclists' need' of a fast and safe traffic flow. The question is how safely to combine both functions, e.g. by determining the characteristics of safe and cyclist-friendly, single bicycle tracks in Zones 30 or in a Shared Space environment.

- *The development of evidence-based design standards for the cycle infrastructure.* Recent developments indicate that cyclists increasingly get injured in crashes without motor-vehicle involvement. This indicates that, in addition to the interactions between motor vehicles and cyclists, the interactions between road users on bicycle tracks are also important. Although crash data is for as yet insufficient, indications are that the unsafe interactions on bicycle tracks are responsible for a major proportion of the seriously injured cyclists. The issue concerns the desired design of bicycle lanes and tracks with respect to safety. In greater detail, the influence on cycling safety of characteristics such as width of the cycle path, track or lane, presence of parking or parked vehicles, cycling intensity, and the presence of mopeds and light-mopeds.

5.5. Evidence-based measures

This and other inventories show that in the Netherlands many road safety measures are implemented without them ever being followed by a study into their effects on safety. As far as known, of those measures that – directly or indirectly – were geared to increasing the safety of cyclists, 17 were evaluated in the area of infrastructure, 6 with respect to enforcement, and 6 regarding vehicle measures. Practically all measures studied indicated a positive effect on road safety. However, it is noticeable that the effects are practically never specified in terms of various modes of transport. Consequently, it is not inconceivable that measures intended to increase the safety of vulnerable road users (for instance Zones 30) may have a positive overall effect, but that this effect especially occurs for car occupants, rather than for vulnerable road users. Thus, evaluation studies should specify the effects of measures per mode of transport.

5.6. Conclusions for the research agenda

In comparison with our knowledge about the underlying causes of the unsafe aspects of motorized traffic, our knowledge about cycling safety is very limited. This implies that a multiplicity of subjects could be investigated, which is not feasible. The agenda could focus

on those groups of cyclists, infrastructure and vehicle characteristics that constitute the major problems.

Cyclists

Noticeable among cyclists is the large proportion of crashes with motor vehicles among secondary school pupils and the continuously increasing proportion of seniors among cycling casualties. In this respect, the following issues require further research.

- Hazard perception is an important condition for safe behaviour. Whether this skill will have been sufficiently developed, especially among 12-14 year-olds, is not known yet. First of all, it should be mapped whether hazard perception among youths is sufficient for them to actually make safe decisions as road users. If this is not the case, it should at least be determined if and how hazard perception can be trained.
- Loss of cycling competence, the physical deterioration due to ageing, and disorders in combination with increasing vulnerability, all underlie senior cyclists' higher risks. Research is required into possibilities for these seniors to be able to still cycle safely.

Bicycles

- Bicycles vary in vehicle characteristics. The question is whether those vehicle characteristics determining safety (e.g. stability and braking force) can be optimized for various target groups.
- The electric bicycle enables higher speeds. The issue is whether these higher speeds cause greater lack of safety, especially for senior cyclists, among whom this type of bicycle is popular.
- Conspicuity and visibility are important prerequisites for safe cycling mobility. Further research is needed into the requirements to be set.
- Concerning the bicycle helmet, the question is how the 'proper way of wearing the qualitatively correct helmet' reduces the risk of brain injuries with particular types of crash.

Cars and lorries as crash opponent

- Electric vehicles make no sound at low speed levels. The question is if and how cyclists and pedestrians make use of sound to timely detect sources of danger.

Infrastructure

- Speed determines the crash risk and its severity. As has earlier been done for pedestrian-car encounters, the principle of 'safe speed limits' should also be applied to bicycle-motor-vehicle encounters, and the consequences for local speed limits should be determined.
- The majority of crashes with cyclists occur on intersections. Given the fact that intersections greatly vary in terms of safety, research is required for the purpose of the optimization of the design, such as the type of physical speed reduction measures, the use of singular bicycle tracks and the transitions between road section and intersection.

- In residential areas the (safe) traffic flow of cycle traffic requires attention. The issue is how residing and flow can be combined in such a situation, for instance, by means of single bicycle tracks.
- The increasing number of seriously injured cyclists as a result of crashes not involving motorized traffic indicates a need for greater insight into the interactions between road users on bicycle tracks.

6. Influence of future developments

Road safety prognoses for 2020 indicate that the developments are particularly unfavourable for cyclists involved in single crashes. These prognoses are based on extrapolations of the development of the road safety of bicycles until 2009 and the implementation of the current Strategic Road Safety Plan with various scenarios for the development of mobility and cuts in infrastructural facilities. The mobility scenarios stem from the Welfare and Habitat (WLO) study. These prognoses were drawn up several years ago and are fairly general. For instance, the prognoses take no account of policy focussing on encouraging bicycle use. As the road safety prognoses are bases on extrapolations of past risks, they do not account for new developments, such as the emergence of electric motor vehicles, the electric bicycle and 'smart' cars. A number of these developments - electric vehicles and bicycles - have been discussed in previous sections and will not further be discussed here.

Because of its social advantages, governments highly encourage the use of bicycles. Certain regions - e.g. the Haaglanden region - aim at increasing the amount of cycling mobility by 20 to 50%. The intensity on cycling facilities, such as bicycle tracks, will increase substantially, and, consequently, so will the interactions and conflicts between cyclists, light-moped riders and other road users who make use of the bicycles tracks. Moreover, the traffic volume on intersections between bicycle tracks will also increase. No studies have been conducted into the consequences for safety and the requirements to be set for cyclist facilities in order to enable such an increase.

In the near future, cars will, as a rule, be equipped with various intelligent applications to facilitate the driving task. This will partly be the effect of the car 'smartly' reacting on information from its environment, and partly because the driver is given information so as to anticipate more successfully. No, or hardly any data is available about the consequences of this development for the safety of the interactions between car drivers and cyclists. It is conceivable that 'intelligent vehicles' behave differently from what cyclists and pedestrians expect on the basis of their previous experiences. Moreover, hardly anything is presently

invested in the options of information technology for the enhancement of cycling safety and cycling comfort. Impact and possibilities for developments should be mapped by systematic research.

With respect to future developments, research ought to focus on the following:

- The question concerns the requirements that should be met by the traffic infrastructure to keep guaranteeing the safety of cyclists, also when cycling mobility substantially increases as a result of the promotion of bicycle use.
- Cars are getting smarter and communicate with each other and their environment. The question concerns the opportunities and threats offered by developments for the safety of non-motorized road users.

7. Methods for cycling research

In studies into the lack of knowledge concerning cycling safety, such as the present one, the methods and techniques available for this type of research should also be examined. Without conducting a thorough analysis of various methods, we can already conclude that the majority of studies make use of crash analyses, questionnaires and observations. Many of the methods applied to car safety have not been developed for cycling safety. No, or hardly any studies have been conducted in which simulators or instrument-equipped bicycles have been used. This section discusses a number of possibilities of innovative research into cycling safety and interventions. Consecutively, the following will be discussed: simulation models focussed on networks and (cycling) facilities, driving simulators to assess bicycle-car interactions, simulations for training purposes and instrument-equipped bicycles.

Simulation models for cycling network development

In contrast with the policy focussed on, for instance, car drivers, cycling policy is mainly developed and implemented on local and regional levels. This implies that cycling policy especially requires regional analyses of cycling issues, and needs data about crashes and measures. With respect to data about infrastructural measures, publications could be made use of, e.g. Ontwerpwijzer Fiets (Cycling Design Indicator). Even then, it remains necessary to be able to assess diverse variants of infrastructural measures with respect to such issues as traffic flow and safety, so that choices can be made on macro-level (network) and micro-level (facilities). Dynamic characteristics and the interactions between road users will mainly determine safety, also cycling safety. Simulation models are regularly used for computing the effects on the flow of car traffic. However, the current simulation models cannot model the effects on safety. This does not only apply to the safety of car traffic, but also that of the cyclist. For this reason, the safety of cyclists plays a minor role in policy-making processes. The reason for the absence of cyclists in these simulation models derives from the limited need for such additions on the international market. It is therefore not to be expected that this addition will be made available through market forces.

Driving and cycling simulators

Driving simulators are used for assessing how car drivers will react in specific traffic situations, and they have significantly contributed to our current knowledge about the way car drivers carry out tasks. Unfortunately, car driver-cyclist interactions have hardly ever been observed in simulators, because the current technique does not make it possible to represent cyclist behaviour reliably. However, we may assume that the new knowledge derived from the world of computer games, in which human movements are presented true-to-life, will make it possible to integrate cycling road users in driving simulators.

In addition to the driving simulators with adequate traffic scenarios for the study of driver responses to cyclists, there is also a need for a 'cycling' simulator to study the responses of cyclists. To date, only very few simulators do exist, but most are based on motorcycle simulators, and the traffic scenarios are not adequate for reflecting the Dutch cycling experience.

Simulation may be an important instrument for studying the effects of potential interventions, and supporting policy-makers with assessing infrastructural solutions and their consequences for cycling safety in the future.

Simulation for training purposes

Simulators are used in many areas for the training of people. This may relate to training with respect to every-day, standard-practice issues, but more often training instances that rarely occur, but which are important and far-reaching. Training the correct reactions to these rare instances can only be done properly by means of simulation. Simulators are also increasingly used for training road users, also for training a specific aspect, such as detecting and reacting on hazards. These training methods are practically solely available for truck and car drivers, and not yet for cyclists and pedestrians. Currently, training of cyclists and pedestrians is mainly based on classical instruction, with only very little actual practice in real traffic. This is the reason why the transfer of training to the real world has shown to be so limited, that the safety effects of these classroom programmes need to be called in question. As practice in real traffic is almost impossible to achieve, the question is how simulation could contribute to the education of (young) cyclists and pedestrians.

Instrument-equipped bicycles

All methods mentioned above try to simulate traffic and reactions by road users as best as possible, and, subsequently, to compare various simulated traffic situations. In order to be able to draw conclusions for real traffic situations on the basis of these methods, the simulation should be true-to-life. This implies that the simulation should correspond with reality. This can only be possible if it is known what 'reality' looks like. These last few years, research into the 'reality' of car drivers has taken a great leap forward. By installing cameras, speed sensors and distance indicators, etc. in hundreds of cars of 'ordinary car drivers', and by collecting data for months on end, greater insight was gained in hazardous traffic situations. By equipping bicycles with instruments in a similar manner, it will be possible to gain better insight in critical encounters and circumstances, as well as in the actual exposure. Owing to the many functions of the current smartphones, such as GPS, gyroscope

and communication features for uploading data, it now seems viable to equip bicycles with instruments relatively easy. This would first of all involve a pilot study, in which it can be investigated whether the instruments are capable of detecting critical circumstances and whether the information is of sufficient quality for further research.

Whereas adequate research instruments are available for motorized traffic, they are almost completely lacking for bicycle traffic. For this reason, cycling studies have until now been limited to field observations and conducting questionnaires.

- In order to upgrade the knowledge development with respect to cycling safety, valid and reliable research instruments should be developed.

8. A top 10 of research priorities

All subjects mentioned above are relevant for the safety of cyclists. Defining the ones that are most important and should be dealt with above all others depends on many factors, such as the magnitude of the problem, the available knowledge about the nature of the problem, the possibilities to take action, the availability of effective measures, the financial prerequisites, the presence of sufficient expertise to conduct the research and the political and social interest in the problem. It is not the objective of this report to prioritize. Yet this section will cluster a number of subjects mentioned above as research themes. They are the following:

1. **Seriously injured cyclists in crashes not involving motor vehicles**
   This type of casualty is on a steep increase in figures, whereas no background data is available in the existing registrations. It should therefore be determined how information about the characteristics of these crashes can be collected reliably.
2. **The development of Safety Performance Indicators for cycling safety**
   Safety Performance Indicators (SPIs) are characteristics of the traffic system determining its safety. They are essential for determining and strengthening the weaknesses in the system prior to crashes occurring. The approach to bicycling safety through SPIs has hardly been applied, because no SPIs have been determined for cyclists. Suggestions for SPIs are the required width of the bicycle track in relation to traffic volumes, or 'safe speeds' in conflicts between bicycles and motor vehicles. Research into the development of SPIs for cycling safety is therefore required.
3. **Protecting cyclists against sustaining injuries**
   Due to the extreme vulnerability of cyclists, it should be investigated how much protection helmets and external airbags offer and how objects causing injuries, such as kerbs, posts and signposts, should be shielded or be designed for greater safety.
4. **Expectations, predictability and behavioural routines with cycling safety**
   The effects should be determined of developments that clash with the expectations, predictability and existing behaviour routines (counter-intuitive developments) of

cyclists and other road users. Examples of these counterintuitive developments are: such as two-sided bicycle tracks, silent motor vehicles and 'smart' vehicles that behave contrary to expectations. E.g., by braking suddenly and unexpectedly.

5. **Hazard perception**
   In contrast to vehicle skills, this higher-order skill develops very slowly. It should be investigated how familiar cycling youths are with hazard perception and how training could enhance it.
6. **Seniors**
   With a view to population ageing, it should be determined how seniors might continue to cycle safely. One of the major questions is whether the benefits of the electric bicycle outweigh possible disadvantages in terms of safety.
7. **Evaluation of measures**
   In order for policy to be based on scientifically determined effects (evidence-based policy), it is necessary to evaluate measures. Evaluation studies ought to differentiate between the effects on the safety of motor vehicles and on those of vulnerable road users.
8. **Developing research instruments**
   Knowledge development and hypothesis-testing research into cycling safety should be upgraded by means of developing valid and reliable instruments.
9. **Converting international findings**
   Not only in the Netherlands, but also abroad, is the safety of cyclists increasingly investigated. To benefit from this knowledge, greater insight is needed in the conversion of this knowledge from international studies.
10. **Interconnections and added value: 1 + 1 = 3**
    Much of the knowledge and many of the studies into the safety of cyclists are relevant for the safety of pedestrians. Facilities meant for seniors also increase the safety of the younger age groups. Moreover, themes 3, 4, 5, 7, and 8 could also be extended to safety for pedestrians. By using the interconnections, knowledge will be generated that can be more widely applied.

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